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Systematic Design Method for Bonded Repair Based on Axiomatic Design Methodology

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Abstract

When cracks along rivet holes and other highly stressed regions of mostly aged aircrafts are found, usually repairs are being made to arrest these cracks. Patches provide an innovative repair technique, which can enhance the way aircrafts are maintained. Composite patch design along with axiomatic design technique deployment is a possibility. Axiomatic Design (AD) is expressed as a system design methodology that is applicable to creation of a new design, analysis and improvement of an existing design. While, here Patch Design system architecture is expressed as application of principles of axiomatic design on top level requirements with consideration of design parameters and constraints. A new conceptual repair process for damaged structures is being developed with zigzagging between AD domains. The full design matrix of repair process will be formed by decomposition of the Composite Patch Repair and systematic step by step presentation of design process. This involves the selection of adhesive material and its thickness, determination of patch dimensions, selection of patch material, repair instructions and finally stress analysis method. It is anticipated that the suggested repair design process will be a useful tool for engineers involved in aircraft maintenance units.

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Keywords: Axiomatic Design; Bonded Repair Methodology; Design Matrix;

1. Introduction

According to CASA definition, all aircrafts are aged even from their date of birth, so aging problem of aircrafts appear from the beginning of their early life and continuous aging operation must get preformed to secure their safety. Moreover of aging aircraft definition, Sahay said Boeing definition of an aircraft is: "Thousands of components and multiple engines, fitted to an airframe, flying in unison; which need to be maintained using ground support equipment so that the aircraft can fly again and again till it is retired or in some unfortunate circumstances rendered incapable of flying [1]." Therefore, all aircrafts need to be maintained and repaired.

In addition to conventional metal repair, bonded repair can also be used to repair aging aircraft structures. To design composite patches, some numerical and analytical methods have been developed which in detail explain the algorithms to approximate the best patch size and stress level in both the patch and skin with implementation of trial and error method. So, in each run, results can be different and will depend on initial values.

For extending the life of aircraft components at reasonable cost, repair of metallic aircraft parts is made instead of replacing damaged parts. The two primary repair methods are Bonded Repair and Mechanically Fastened Repair [2]. Both types of repairs have their pros and cons, but The Bonded Repair technology has considerable advantages over the other, such as high stiffness, light weight, corrosion resistance and installation without causing additional damages. By selecting Bonded Repair method, patch and adhesive material selection, patch design, surface preparations and pre/post repair flaw inspection are major factors which must be considered [3]. Each of these steps is based on some criteria.

Axiomatic Design is a systematic design methodology with aid of matrixes that was developed by Nam Pyo Suh at MIT [4]. As long as, no research results related to the application of Axiomatic Design methodology to the Patch Repair have

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been found yet by the authors in the literature, some of methods of Composite Bonded Repair will be introduced and shortly reviewed here. Avram presented a process that comes from the Guidelines for Composite Repair to Metallic Structures handbook [5]. This process describes patch sizing using stiffness ratio and the analysis of critical area such as patch tip stress, adhesive shear strain, peel stress, and stress intensity factor. Avram also gives some rules of thumb for patch and adhesive material selection and surface preparation.

Doung and Wang provided a process which iteratively searches for the first design that meets the criteria, since the results will be different depending on the rout that the searching process has taken and it does not necessarily secure the optimal design [2]. While in the first step of the method criteria for cracked skin, patch and adhesive are defined, in the second step patches and adhesives materials are selected, and finally, an iterative process which meets the criteria is performed to find a design. Designed repaired will be subjected to mechanical or thermo mechanical loads to determine patch dimensions/size.

Marioli-riga and Gdoutos presented a step by step process analysis for composite patch repair [6]. This process was presented in a systematic way which included damage inspection, material selection, stress analysis and design of repair, surface preparation, validation test and airworthiness. The methodology is based on Rose's equations and finite element analysis of the repaired cracked plate.

This paper concentrates on application of Axiomatic Design method for Bonded Repair to develop a framework for design of composite patches. In next section decomposition of domains in AD are described and will be followed by identifying of Full Design Matrix. An example of a patch design problem for C-5A aircraft will be solved by new methodology of systematic design.

2. Explanation of Axiomatic design method

Axiomatic design method starts with customer needs and expectations that translated to top level functional requirements then to top level design parameters and also top level process variables. Each of these four characteristics forms a domain. These domains are so called Customer, Functional, Physical and Process domains. The domains are decomposed from highest level of conceptual design to detailed design, hierarchically. After assigning the top level requirement(s) to design parameters at the same level, functional requirements will be decomposed and mapped back to their design parameters but at a lower level. This zigzag process continues between domains until design is completely decomposed [7] and design matrix is extracted. This process has been done here for Bonded Repair Design Technology.

2.1. Step 1: Customer Needs(CN)

Maintenance process has been done by MRO (Maintenance, Repair, and overhaul) organizations. So, the main customers of Bonded Repair are MRO organizations [1]. According to the definition of Boeing given above, primary need of this customer is performing scheduled and unscheduled maintenance. So, we can translate this need to:

CN0 (Top-Level): Restore Strength of Damaged Component.

2.2. Step 2: Top-level Functional Requirements (FR) and Design Parameters (DP)

While the highest level of Functional Requirement that meets the Customer Needs and Design Parameters will shape the form of Design Matrix for Bonded Repair, the lower-levels of decomposition will lead to Repair Methodology. Given description results in following statements for top level of FR and DP:

FR0: Reinforce the Damaged Surface

DP0: Composite Bonded Repair Technology

2.3. Step 3: Zigzagging between FRs and DPs

Damaged surface reinforcing involves a collection of tasks. In this context, reinforcing involves all of the patch design steps, and repair process. So, the decomposed FR0 to two sub functions and equivalent Design Parameters, are shown in Table 1.

Table 1.The first level decomposition of FR0.

	FR	DP
1	Design of repair	Reinforcing element
2	Implement repair process	Detail of step by step repair process

Equation 1 as the first level design equation is the immediate result of Table 2 and as expected its matrix demonstrates a decoupled design.

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} x & o \\ x & x \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \quad (1)$$

But during its implementation to a specific problem following constraints and optimization criteria should be taken into consideration:

Table 2. Constraints and optimization criteria of the first level.

Constraints:	FRs	
	1	2
Doing repair without creating further damage or weak link	x	x
Optimization criteria:		
Minimize weight of repair	x	
Maximize safety	x	x

Now using DP1, FR1 should be decomposed as shown in Table 3. Therefore, Design of Repair has broken down to Load Transfer Path, Load Sustainment Element, and Evaluation of Repair Design and again the equivalent DPs are generated simultaneously [4] and the resulting Design Matrix is shown in Equation 2.

Table 3. The second level decomposition of FR 1.

	FR	DP
1.1	Transfer loads to reinforcing element	Adhesive
1.2	Sustain the external load on reinforcing element	Composite patch
1.3	Evolution of repair design	Stress analysis of reinforcing element

$$\begin{Bmatrix} FR1.1 \\ FR1.2 \\ FR1.3 \end{Bmatrix} = \begin{bmatrix} x & o & o \\ x & x & o \\ x & x & x \end{bmatrix} \begin{Bmatrix} DP1.1 \\ DP1.2 \\ DP1.3 \end{Bmatrix} \quad (2)$$

Once again, it is a decoupled Design Matrix.

As process progresses to the third level, the decomposition of FR 1.1 yields to Table 4 and the resulting Design Matrix is shown in Equation 3, while satisfying the constraints listed in Table 5.

Table 4. The third level decomposition of FR 1.1.

	FR	DP
1.1.1	Plasticity Resistance Due to Thermal Loads (Minimize thermal residual stress in both the patch and Damaged Surface [3])	Cure Temperature of Adhesive
1.1.2	Plasticity Resistance of Adhesive due to Shear Loads	Shear Yield Stress of Adhesive
1.1.3	Transfer Stress from Damaged Surface to the Patch	Shear Modulus of Adhesive
1.1.4	Possibility of Adhesive Usage	Operating Temperature of Adhesive
1.1.5	Increase Load Transferring Capacity	Thickness of Adhesive

$$\begin{Bmatrix} FR1.1.1 \\ FR1.1.2 \\ FR1.1.3 \\ FR1.1.4 \\ FR1.1.5 \end{Bmatrix} = \begin{bmatrix} x & o & o & o & o \\ x & x & o & o & o \\ x & o & x & o & o \\ x & o & o & x & o \\ o & x & x & x & x \end{bmatrix} \begin{Bmatrix} DP1.1.1 \\ DP1.1.2 \\ DP1.1.3 \\ DP1.1.4 \\ DP1.1.5 \end{Bmatrix} \quad (3)$$

Table 5. Constraints for FR1.1/DP1.1.

Constraints:	FRs				
	1.1.1	1.1.2	1.1.3	1.1.4	1.1.5
load carrying capability equal or greater than parent material		x	x		x
Operating Temperature range: $-50^oC\ to +80^oC$ [8]				x	
Selection Criteria:					
Lowest Possible Cure Temperature [8]	x				

Also, at this level, the decomposition of FR 1.2 for composite patch gives Table 6 and decoupled matrix of Equation 4.

Table 6. The third level decomposition of FR 1.2.

	FR	DP
1.2.1	Increase Capability of the Patch	Patch material attributes
1.2.2	Reduce Stress Intensity on the Patch	Patch dimensions

$$\begin{Bmatrix} FR2.2.1 \\ FR2.2.2 \end{Bmatrix} = \begin{bmatrix} x & o \\ x & x \end{bmatrix} \begin{Bmatrix} DP2.2.1 \\ DP2.2.2 \end{Bmatrix} \quad (4)$$

In order to select proper material, the function FR1.2.1 is decomposed to Increasing Strength and Reducing Failure and implicitly two types of loading should be considered: Mechanical and Thermal. Considering these requirements the result are as shown in Table 7.

Table 7. The forth level decomposition of FR 1.2.1.

	FR	DP
1.2.1.1	Increase Patch Ultimate Strength	Ultimate Strength of Patch
1.2.1.2	Increase Patch Stiffness	Young's Modulus of Patch
1.2.1.3	Reduce Deformation of Material during Mechanical Loading [2]	Poison Ratio of Patch
1.2.1.4	Reduce Thermal Residual Stress caused during Thermal Loading [3]	Coefficient of thermal expansion of Patch
1.2.1.5	Endure the Galvanic Corrosion [3]	Non-conductivity of Patch

$$\begin{Bmatrix} FR1.2.1.1 \\ FR1.2.1.2 \\ FR1.2.1.3 \\ FR1.2.1.4 \\ FR1.2.1.5 \end{Bmatrix} = \begin{bmatrix} x & o & o & o & o \\ o & x & x & o & o \\ o & x & x & o & o \\ o & o & o & x & o \\ o & o & o & o & x \end{bmatrix} \begin{Bmatrix} DP1.2.1.1 \\ DP1.2.1.2 \\ DP1.2.1.3 \\ DP1.2.1.4 \\ DP1.2.1.5 \end{Bmatrix} \quad (5)$$

Equation 5 also represents this level of decomposition. As, FR 1.2.1.2 and FR 1.2.1.3 are closely coupled, the design matrix is not yet decoupled. It seems that the nature of these parameters is coupled. So, these two DPs for plane stress can be merged into a new variable as presented in Equation 6:

$$D = \frac{E}{1-v^2} \quad (6)$$

This new variable translated to Equivalent Elasticity Modulus. So, this level's decoupled design matrix is expressed as Equation 7, and Constraints for patch material selection are shown in Table 9.

Table 8. The forth level decomposition of FR 1.2.1.

	FR	DP
1.2.1.1	Increase Patch Ultimate Strength	Ultimate Strength of Patch
1.2.1.2	Increase Stiffness and Reduce Deformation of Patch Material	Equivalent Elasticity Modulus
1.2.1.3	Reduce Thermal Residual Stress caused during Thermal Loading [3]	Coefficient of thermal expansion of Patch
1.2.1.4	Endure the Galvanic Corrosion [3]	Non-conductivity of Patch

$$\begin{Bmatrix} FR1.2.1.1 \\ FR1.2.1.2 \\ FR1.2.1.3 \\ FR1.2.1.4 \end{Bmatrix} = \begin{bmatrix} x & o & o & o \\ o & x & o & o \\ o & o & x & o \\ o & o & o & x \end{bmatrix} \begin{Bmatrix} DP1.2.1.1 \\ DP1.2.1.2 \\ DP1.2.1.3 \\ DP1.2.1.4 \end{Bmatrix} \quad (7)$$

Table 9. Constraints for FR1.2.1/DP1.2.1.

Constraints:	FRs			
	1.2.1.1	1.2.1.2	1.2.1.3	1.2.1.4
Maintain Stiffness Ratio (SR) Greater than One		x		
Match the Thermal Properties of the Patch and the Parent structure			x	

After patch material selection, the patch dimensions will be determined. Also, reduction of normal and shear stresses at tip of the patch should be considered at this level. The decomposition of requirements is shown in Table 10 and Constraints govern the mapping from functional requirements to design parameters are shown in Table 11.

Table 10. The forth level decomposition of FR 1.2.2.

	FR	DP
1.2.2.1	Reduce Bending induced by Neutral Load Axis Shift [3]	Patch Thickness
1.2.2.2	Reduce shear stress to resist creep [2]	Patch Overlap Length
1.2.2.3	Reduce adhesive peel stress of the repair patch tips [6]	Patch Taper Length
1.2.2.4	Reduce the skin stress near the patch tip [5]	Patch Aspect Ratio

A decoupled design at this level is shown in Equation 8.

$$\begin{Bmatrix} FR1.2.2.1 \\ FR1.2.2.2 \\ FR1.2.2.3 \\ FR1.2.2.4 \end{Bmatrix} = \begin{bmatrix} x & o & o & o \\ x & x & o & o \\ x & x & x & o \\ o & o & x & x \end{bmatrix} \begin{Bmatrix} DP1.2.2.1 \\ DP1.2.2.2 \\ DP1.2.2.3 \\ DP1.2.2.4 \end{Bmatrix} \quad (8)$$

Table 11. Constraints for FR1.2.2/DP1.2.2.

Constraints:	FRs			
	1.2.2.1	1.2.2.2	1.2.2.3	1.2.2.4
Reduce out of plane bending due to neutral axis shift [5]	x			
Taper slope of approximately 1:10 [8]		x		
Overlap Distance of 30-80 times of Parent Material Thickness [8]			x	

For evaluate the Repair Design (FR 1.3), this level of decomposition should be followed. This level measures repair effectiveness via four parameters. The decomposition of Evaluation of design repair is shown in Table 12. Equation 9 also represents this level of decomposition.

Table 12. The third level decomposition of FR 1.3.

	FR	DP
1.3.1	Reduce out of Plane Bending	Patch Tip Stress
1.3.2	Reduce Stress Intensity [5]	Effectiveness of the Repair
1.3.3	Increase Ultimate Strength of the Material [5]	Patch Stress
1.3.4	Increase Quality of Bond Line	Maximum Shear Strain in the Adhesive

$$\begin{Bmatrix} FR1.3.1 \\ FR1.3.2 \\ FR1.3.3 \\ FR1.3.4 \end{Bmatrix} = \begin{bmatrix} x & o & o & o \\ x & x & o & o \\ x & o & x & o \\ x & o & o & x \end{bmatrix} \begin{Bmatrix} DP1.3.1 \\ DP1.3.2 \\ DP1.3.3 \\ DP1.3.4 \end{Bmatrix} \quad (9)$$

Although, the decomposition can go on till detailed level of design, the decomposition of first branch at fourth level is thorough enough. Product of this branch decomposition is the design criteria for Reinforcing Element [5]. In order to complete the Bonded Repair Methodology, the Second branch (FR2 / DP2) should be followed. Implementation of maintenance can be decomposed to Surface Preparation, Element Manufacturing, Inspection of Element and other functions. Surface Preparation is the most critical step in Bonded Repair process. There are four types of surface preparation techniques including PAA, PACS, GBS, and GB Sol-gel [9]. GBS and GB Sol-gel methods have advantage of not using any acids on the aircraft [10]. So, the third branch decomposition is done according to the methods.

Table 13. The second level decomposition of FR2.

	FR	DP
2.1	Inspect Damaged Surface	Pre-processing Equipment
2.2	Manufacture Reinforcement Element	Manufacturing Equipment
2.3	Prepare Plate for Reinforcing	Preparation Equipment
2.4	Place and Cure the Reinforcement Element	Placing and Curing Equipment
2.5	Seal Reinforcement Element	Sealing Equipment (like aluminum foil tape) [11]
2.6	Check Bond Quality	Inspection Equipment (like eddy current, X-ray, and Ultrasonic)

$$\begin{Bmatrix} FR2.1 \\ FR2.2 \\ FR2.3 \\ FR2.4 \\ FR2.5 \\ FR2.6 \end{Bmatrix} = \begin{bmatrix} x & o & o & o & o & o \\ o & x & o & o & o & o \\ x & o & x & o & o & o \\ x & x & x & x & o & o \\ o & o & x & x & x & o \\ x & x & o & o & o & x \end{bmatrix} \begin{Bmatrix} DP2.1 \\ DP2.2 \\ DP2.3 \\ DP2.4 \\ DP2.5 \\ DP2.6 \end{Bmatrix} \quad (10)$$

Table 13 and Equation 10 present this decomposition. Surface inspection should be performed to provide more detailed information on damaged area surface [5]. So, decomposition of FR 2.1 is as shown in Table 14 and Equation 11.

Table 14. The third level decomposition of FR2.1.

	FR	DP
2.1.1	Clean the Damaged Area by Smoothing the Jagged Edges [11]	Smoothening Tools (like sanders)
2.1.2	Measure Length of Crack	Crack Measurement System
2.1.3	Analysis Damaged Surface	Analysis Tools

$$\begin{Bmatrix} FR\,2.1.1 \\ FR\,2.1.2 \\ FR\,2.1.3 \end{Bmatrix} = \begin{bmatrix} x & o & o \\ x & x & o \\ o & o & x \end{bmatrix} \begin{Bmatrix} DP\,2.1.1 \\ DP\,2.1.2 \\ DP\,2.1.3 \end{Bmatrix} \quad (11)$$

Also, Analysis of Damaged Surface can be decomposed into three main parts as shown in Table 15 and Equation 12.

Table 15. The first level decomposition of FR 2.1.3.

	FR	DP
2.1.3.1	Determine Loading Mode of Damaged Surface	FEM Analysis of Damaged Surface
2.1.3.2	Measure Thickness of Damaged Surface	Measurement Instrument
2.1.3.3	Identify Material of Damaged Surface	Material Identification Instrument

$$\begin{Bmatrix} FR\,2.1.3.1 \\ FR\,2.1.3.2 \\ FR\,2.1.3.3 \end{Bmatrix} = \begin{bmatrix} x & o & o \\ o & x & o \\ o & o & x \end{bmatrix} \begin{Bmatrix} DP\,2.1.3.1 \\ DP\,2.1.3.2 \\ DP\,2.1.3.3 \end{Bmatrix} \quad (12)$$

Equation 12 is an uncoupled design matrix (Equation 12). Loading modes, thickness, and material type are all parameters of analyzing damaged surface. Loading Modes of damaged surface includes “Opening Mode”, “Sliding Mode”, and “Tearing Mode”.

After inspection of damaged area, the reinforcing element should be manufactured. The decomposition of FR 2.2 can be stated as in Table 16and Equation 13.

Table 16. The third level decomposition of FR 2.2.

	FR	DP
2.2.1	Place Uncured Patch in Proto-Clave	Teflon Sheet
2.2.2	Remove Trapped Air in the Bond Line	Sealed Vacuum Bag
2.2.3	Cure Patch with High Pressure and Temperature	Cure Equipment (like Autoclave)
2.2.4	Inspect the Fabricated Patch for any Flaws or Voids	Ultrasonic Inspection System

$$\begin{Bmatrix} FR\,2.2.1 \\ FR\,2.2.2 \\ FR\,2.2.3 \\ FR\,2.2.4 \end{Bmatrix} = \begin{bmatrix} x & o & o & o \\ o & x & o & o \\ o & o & x & o \\ o & o & o & x \end{bmatrix} \begin{Bmatrix} DP\,2.2.1 \\ DP\,2.2.2 \\ DP\,2.2.3 \\ DP\,2.2.4 \end{Bmatrix} \quad (13)$$

After manufacturing of the reinforcing element, damaged area should be prepared for installation. So, Preparation of Damaged Surface for reinforcing is decomposed as in Table 17 and Equation 14.

Table 17. The third level decomposition of FR 2.3.

	FR	DP
2.3.1	Remove any Particles from the Surface	Cleaning Agent
2.3.2	Enhance Bond Durability	Chemical Treatment
2.3.3	Prevent Contamination and improve Long-term Durability [11]	Primer

$$\begin{Bmatrix} FR\,2.3.1 \\ FR\,2.3.2 \\ FR\,2.3.3 \end{Bmatrix} = \begin{bmatrix} x & o & o \\ o & x & o \\ o & o & x \end{bmatrix} \begin{Bmatrix} DP\,2.3.1 \\ DP\,2.3.2 \\ DP\,2.3.3 \end{Bmatrix} \quad (14)$$

Following to reinforcement manufacturing and surface preparation, the patch is implemented. Installation of the element on the plate can be stated as in Table 18 and Equation 15.

Table 18. The third level decomposition of FR 2.4.

	FR	DP
2.4.1	Accurate Placement of the Patch in the Middle of the Panel [5]	Marking Tools
2.4.2	Abrade the Area [5]	Grit Blast
2.4.3	Preparation of Adhesive [5]	Adhesive Preparation Tools
2.4.4	Place and Keep the Patch from sliding around [5]	Flash Breaker
2.4.5	Cure the Repaired Panel [5]	Curing Equipment

$$\begin{Bmatrix} FR\,2.4.1 \\ FR\,2.4.2 \\ FR\,2.4.3 \\ FR\,2.4.4 \\ FR\,2.4.5 \end{Bmatrix} = \begin{bmatrix} x & o & o & o & o \\ o & x & o & o & o \\ o & o & x & o & o \\ x & o & o & x & o \\ o & o & o & o & x \end{bmatrix} \begin{Bmatrix} DP\,2.4.1 \\ DP\,2.4.2 \\ DP\,2.4.3 \\ DP\,2.4.4 \\ DP\,2.4.5 \end{Bmatrix} \quad (15)$$

The repair process will be completed after element sealing and repair inspection.

2.4. Step 4: Identify Full Design Matrix (DM)

The full design matrix created by decomposition of composite Bonded Repair is shown in Fig. 1. Full design matrix. This matrix is reordered and the result presents an improved sequence for design steps which reduces and even eliminates classic inconvenient iterations.

Design Matrix			2.1					1.1					1.2												2.2				2.3			2.4						
			2.1.1	2.1.2	2.1.3			1.1.1	1.1.2	1.1.3	1.1.4	1.1.5	1.2.1				1.2.2				1.3.1	1.3.2	1.3.3	1.3.4	2.2.1	2.2.2	2.2.3	2.2.4	2.3.1	2.3.2	2.3.3	2.4.1	2.4.2	2.4.3	2.4.4	2.4.5	2.5	2.6
					2.1.3.1	2.1.3.2	2.1.3.3						1.2.1.1	1.2.1.2	1.2.1.3	1.2.1.4	1.2.2.1	1.2.2.2	1.2.2.3	1.2.2.4																		
2.1	2.1.1		X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
	2.1.2		X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
	2.1.3	2.1.3.1	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
		2.1.3.2	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
		2.1.3.3	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
1.1	1.1.1		O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
	1.1.2		O	O	O	O	O	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
	1.1.3		O	O	O	O	O	X	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
	1.1.4		O	O	O	O	O	X	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
	1.1.5		X	O	O	O	O	O	X	X	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
1.2	1.2.1	1.2.1.1	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
		1.2.1.2	O	O	O	X	O	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
		1.2.1.3	O	O	O	O	O	X	O	O	X	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
		1.2.1.4	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
	1.2.2	1.2.2.1	X	O	O	X	X	O	O	O	O	O	O	X	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
		1.2.2.2	X	O	O	O	O	O	X	X	X	O	O	O	O	O	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
		1.2.2.3	O	O	O	O	O	X	O	X	O	X	O	X	O	O	X	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
		1.2.2.4	O	O	O	O	O	X	O	O	X	O	O	O	X	O	O	O	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
1.3.1			O	O	X	O	X	X	O	O	X	O	O	O	X	O	X	O	O	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
1.3.2			X	O	X	X	X	X	O	X	O	X	O	X	X	O	X	X	O	X	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
1.3.3			O	O	X	O	O	O	O	O	O	O	X	X	O	O	X	X	O	X	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
1.3.4			O	O	X	X	X	O	X	X	X	X	O	O	O	O	X	X	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O
2.2	2.2.1		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O
	2.2.2		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O
	2.23		O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	X	O	X	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O
	2.2.4		O	O	O	O	O	O	O	O	O	O	X	X	X	X	X	X	X	X	X	O	X	O	O	O	X	X	O	O	O	O	O	O	O	O	O	O
2.3	2.3.1		X	X	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O
	2.3.2		O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O
	2.3.3		O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O	O
2.4	2.4.1		X	X	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	X	O	O	O	O	X	O	O	O	O	O	O	X	O	O	O	O	O	O
	2.4.2		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	X	O	O	X	O	X	O	X	O	O	O	O	O
	2.4.3		O	X	O	O	O	O	O	O	X	X	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	X	X	O	O	X	O	O	O	O
	2.4.4		X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	X	O	O	O
	2.4.5		O	O	O	X	X	X	O	O	X	O	O	O	X	O	O	O	O	O	X	X	O	X	O	O	O	O	O	O	X	O	O	O	O	X	O	O
2.5			O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O
2.6			X	X	X	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	X	X	X	X	X	X	O	O	O	O	O	O	O	O	O	O	O	X

Fig. 1. Full design matrix

3. Example: C-5A Crack patching

To evaluate accuracy and profits of introduced method, it is applied to repair process of an aged C-5A and the result compared to other repair alternatives. One of the known issues with C-5A is multiple small-cracks in the upper aft-crown section of the fuselage skin. Usually the cracks are believed to have created by rivet holes due to highly stress or stress corrosion of the aluminum skins [12].

In the first step, the Customer Needs should be defined and translated to top level Functional Requirements. Here, structural reinforcement on the cracked fuselage is the customer need. The next step is Repair Implementation process according to full Design Matrix of bonded repair process introduced earlier. Therefore, details of procedure used in this example are as bellow:

- Analysis of damaged surface

Clean the damaged area by smoothing the jagged edges and measure the length of crack. Also, determine loading mode, thickness and material of damaged surface. In this example, the C-5A crown section is subjected to longitudinal tensile bending in addition to biaxial tension, Also, Aluminium7079-T6 is material of fuselage skin [2, 12].

- Adhesive Selection

According to Full Design Matrix, the first criterion for adhesive selection, which is an independent design parameter, is its cure temperature which must be between 93 and 121°C [2]. Thereafter, other Adhesive selection criteria should be chosen in the sequence defined by matrix usually with consideration of cure temperature.

Table 19. Adhesives properties [2]

Adhesive	Cure Temp. (Time)	One ply Thickness	Environment	Shear modulus	Shear yield stress	Max shear strain
FM-73	121(2h)	0.114	RT/dry	355.1	35.5	0.6
FM-300-2K	121(1.5-2h) or 177(1.5h)	0.152	RT/dry	465.4	38.6	0.3
AF-163-2K	121(1h)	0.13	NA	405.8	39.3	0.58

According to Table 19, all of three adhesives have good strength in the expected operation range and high shear modulus that can reduce the stress in both the patch and plate [1]. So, FM-73 has been chosen because of minimum adhesive thickness.

- Patch material selection

Factors considered in patch material selection are independent of each other which make the material selection process a sequence free approach. Therefore, materials have been initially ranked by eddy current based on conductivity, and then strength and stiffness, and finally considering their CTE difference. Due to the rankings the weakest ones opted out so the remaining ones are highlighted in Table 20.

Table 20. Patch material properties [2, 5, 9]

Material	$\alpha(\times 10^6/°C)$	D (GPa)	σ_{ult} (GPa)	Thickness (mm)	Conductivity
Al 2024-T3	0	81.25	0.324	0.5	0
Boron/Epoxy	4.8	216.10	1.59	0.127	1
GLARE 2	17.9	73.62	0.39	1.549	1
Graphite/epoxy	23.7	143.75	1.447	0.137	0
Glass/Epoxy	16.6	54.95	1.13	0.25	1
AS4/3501-6 Carbon/Epoxy	23.5	162.64	2.137	0.125	0
T300/5208 Carbon epoxy	23.47	140.07	1.513	0.3	0
SCS-6/Ti-15-3	16.55	238.38	1.517	NA	0
S-2 glass/epoxy	15.86	46.92	1.724	0.127	1

Although two remaining materials at this level are considerable, introduction of the final choice will be postponed until more detailed calculations as presented in following steps is done. However, it is interesting to know that in two known methods by Guijt and Verhoeven [12] and Doung and Wang [2] the suggested patch material for the identical problem is also GLARE2.

- Patch dimensions

To approximate the patch sizes, Repair Guidelines are used and dimension of patch has been determined [5]. The repair design is shown in Fig. 2.

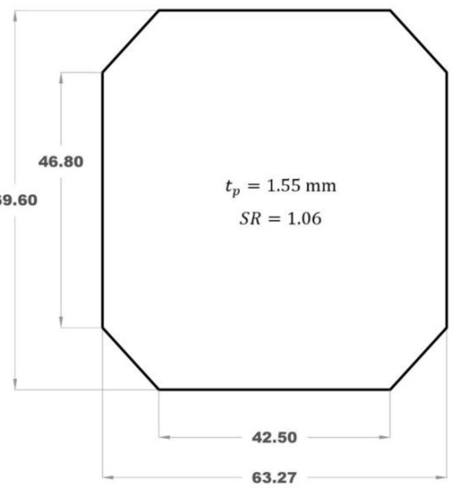

Fig. 2. Patch configuration

- Repair effectiveness

Finally, stress in the patch and skin have been calculated and compared with the maximum allowed values. Table 21shows the criteria that the repair should satisfy.

Table 21. Checking the effectiveness of the patch

DPs	Condition	Equations
Patch tip stress	$\sigma_{\text{tip}} < \sigma^{s}_{ultimate}$	$\sigma_{tip} = \Omega\sigma_{applied} + [E_s((\alpha_s - \alpha_{eff})(RT - T_{eff}) + (\alpha_p - \alpha_s)(T_{oper} - RT))]$
Effectiveness of the repair	$K_{repaired} < K_{IC}$	$K_{repaired} = \sigma_{under}(= \frac{E_s t_s}{E_p t_p + E_s t_s}\sigma_{tip})\sqrt{\frac{E_s t_s \beta t_A}{G}}$
Patch stress	$\sigma_{\text{patch}} < \sigma^{p}_{ultimate}$	$\sigma_{patch} = SR\sigma_{tip}$
Maximum shear strain	$\lambda_{Adhesive} < \lambda^{A}_{max}$	$\lambda_{Adhesive} = \frac{\sigma_{under} t_s \beta}{G}$

According to the calculation, it is obvious, if Boron Epoxy chosen as a patch material, repair effectiveness criteria does not satisfy all the conditions, so the only remaining choice for patch material is GLARE2 as was suggested by the previously mentioned methods.

- Repair process

At this stage, bonding surface of aircraft body is prepared and the patch is fabricated. The patch is then placed upon damaged surface and cured. After curing, the repair is inspected to check bond quality.

Finally, the results of the Axiomatic Design method compared with two other references mentioned earlier, see Table 22.

Table 22. Comparison of the result

Parameters	Ref [12]	Ref [2]	Axiomatic Design
Adhesive	AF-163-2M	FM-73	FM-73
Patch Material	Glare 2-4/3	Glare 2-4/3	Glare 2-4/3
Patch Thickness	1.55 mm	1.55 mm	1.55 mm
Number of ply	1-ply	1-ply	1-ply
Overlap length	NA	NA	34.8 mm
Taper length	0 (1-ply)	0 (1-ply)	0 (1-ply)
Patch length	100 mm	60.2 mm	69.6 mm
Patch Width	89.9 mm	59.4 mm	63.27mm

As this table shows, the result of axiomatic design method in bonded repair is mostly the same as the two mentioned classical methods. Though, negligible differences in patch dimensions with reference [12] that may be the result of different factors of safety. A quick comparison suggests validity of Axiomatic Design method introduced to this field in the present paper.

4. Conclusion

In this paper, the Axiomatic Design theory applied to Bounded Repair, allowed a much faster design process, with less cost and uncertainties in comparison with other methods specially try and error approach. So, Axiomatic Design is a valuable design tool that helps creation of systems meet the requirements.

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